1. Introduction

The Consumer Electronics Manufacturers Association, a sector of the Electronic Industries Association (EIA/CEMA), has requested a study to analyze the technical merits of terrestrial gap-fillers to supplement the coverage of a satellite Digital Audio Radio Broadcast Service (DARS) and to analyze the impact of the system carrier frequency in the range covering L-band (1452-1492 MHz) and S-band (2310-2360 MHz) on the characteristics of such systems.

The Communications Research Centre ("CRC") has developed, over the years, a wealth of expertise in the fields of propagation, satellite broadcasting as well as terrestrial broadcasting. In particular, it has developed expertise in the digital transmission of these broadcast signals in various channel environments. This report presents the findings related to the key technical merits of using terrestrial gap-fillers to complement satellite DARS systems and the impact of the operating frequency, in the range of 1452 MHz to 2360 MHz, on their effectiveness and on the relative complexity of their implementation.

Following are the results of an analysis done through a literature survey, application of scientific and technical knowledge, overview of results from studies previously conducted at CRC and gathering of opinions from CRC experts in the various related fields.

2. Background

This analysis was done at the request of EIA/CEMA to better understand the interrelationship of many parameters affecting deployment of terrestrial gap-fillers to complement satellite DARS. The FCC REPORT AND ORDER, MEMORANDUM OPINION AND ORDER AND FURTHER NOTICE OF PROPOSED RULEMAKING, IB Docket No. 95-91 solicits comments on DARS licensees use of gap-fillers to meet their service requirements.

Further, the provision of a seamless coverage for satellite broadcasting of DARS was stated in the report presented to the FCC by the satellite DARS Pioneer's Preference Review Panel [REP-96].

In this report, it was stated that:

> *"From a Listener's Standpoint, Radio Broadcasting Should be "Seamless"*
>
> *A radio broadcaster defines a coverage area for his broadcasts. Whether this be a small, local coverage area of tens of square miles, or all or most of the U.S., as in DARS proposals, or anything in between, the listeners of the broadcasts expect "seamless" reception. That is, an uninterrupted, high quality signal is expected everywhere within the coverage area as defined by the coverage contours for the particular service.*
>
> *Such an availability requirement within the broadcast coverage area is especially important for mobile reception. Listeners in cars and trucks do not want a signal dropping in and out within their driving locality."*

It was also stated that:

> *"After careful review of the designs presented in the documents, we find that "gap fillers" will be necessary to serve areas "seamlessly" for these designs. Once this is understood, the satellite signal delivery techniques described become no more than different ways of minimizing the local level of dependence on "gap fillers". In particular, the number and power levels required to combat the effects of building and foliage blockage will vary among the designs."*

The **need for seamless coverage** for DARS has been clearly established along with the **need for terrestrial gap-fillers** to actually implement it. The present report discusses the various technologies and implementation means available in trying to achieve this goal. There are a number of technical constraints that define the use and the extent of coverage of terrestrial gap-fillers supplementing satellite DARS. These are related to the frequency used by the service, the speed of the vehicle for which the service has to be provided, the complexity of the transmission infrastructure and the complexity of the technology to be used in the receivers.

3. Service objectives for DARS systems

3.1 High quality digital audio

The introduction of a new audio broadcasting service will be successful if consumers perceive an obvious advantage, be it in sound quality, in service availability, in the type of service offered, or in the cost. From the technical point of view, digital coding is necessary to bring CD or near CD audio quality to the consumer. As a matter of fact, digitization of radio broadcasting chains is now in an advanced state, in many cases leaving only the last link to the public, that is the exciter, RF amplification and emission elements, in analog form.

Advanced audio source coding is used to reduce the bit rate in an attempt to maximize the use of radio frequency spectrum for sound broadcasting. It has been established, through subjective assessment testing done through the EIA/CEMA DAR Subcommittee system tests, that bit rates in the range 160 kbit/s to 256 kbit/s are necessary to reproduce stereophonic audio quality equivalent to Compact Discs [EIA-95]. For this discussion, it will be assumed that 256 kbit/s is needed per radio program to provide one CD-Quality stereophonic program (224 kbit/s) along with some 32 kbit/s ancillary data services.

3.2 Vehicular and portable reception

Today, a large percentage of the audience for sound broadcasting is made of people in transit, in their car or in public transportation. Digital sound broadcasting is already available for fixed reception through cable and satellite distribution. The DAR service is therefore aimed at addressing predominantly the mobile and portable segment of the audience. In fact, if it was to address only fixed reception where antennas can be aimed once at the satellite, the use of higher frequency bands with the possibility of relying on more directive antennas at both transmit and receive ends, such as the DSR system in Germany [ITU-90a], would make for better use of the spectrum. The principal merit of L and S-bands is that omnidirectional antennas can be used at the reception, allowing mounting of simple non-tracking antennas on cars and use of portable and wearable (e.g., walkman) receivers.

3.3 High service availability

On the basis of previous work done on digital sound broadcasting, it is evident that a graceful failure in audio service performance is difficult to achieve with digital modulation. Effective channel coding and digital modulation are inherently designed to keep the Bit-Error-Rate (BER) below a threshold, beyond which the audio quality degrades rapidly. It was found, through the EIA/CEMA DAR Subcommittee laboratory tests [EIA-95], that only a small differential (in the order of a few dB's) in received power exists between perfect audio received quality and unusable service quality.

Due to the abrupt failure characteristic of digital modulation, it will be necessary to ensure that reception is more reliable than in the cases of conventional AM and FM services. This can be achieved with a proper level of excess field strength available throughout the service area, especially where signal fading is likely to occur. Unlike with conventional FM, where the service availability was set at 50% locations and 50% time, F(50,50), the availability of the new DARS service will be needed to be in the range of 90% to 99% of locations and time to compensate for the abrupt failure characteristic mentioned above.

In this work, the location availability will be assumed to be 95% for the purpose of the field strength propagation predictions. It is believed that, if multiple gap-fillers are used in a proper fashion to blanket a given area, the gain obtained by this transmit diversity will bring the actual service availability in the neighbourhood of 99%.

3.4 Seamless coverage

Adequate vehicular and portable reception is a fundamental requirement and because it is the most demanding receiving condition, the system has to be designed to meet this objective, considering that other modes of reception (i.e. fixed, transportable (boombox), wearable (walkman), etc.) should then be automatically covered. The mobile audience will expect uninterrupted high quality signal reception everywhere, within reasonable limits, in the service area. This "seamless" reception can be translated into a high service availability figure (e.g., 99% of locations and time) not only on highways but everywhere in the service area where mobile receivers are used.

3.5 Summary of service objectives:

The service objectives for a new DARS system can be summarized as follows:

- High quality audio and capability for new data services
- Vehicular and portable reception
- 99% service availability everywhere in the service area

In order to meet these objectives, the most advanced techniques must be employed in each and every component of the broadcasting system: audio coding, channel coding, modulation, transmission, receiver design, etc.

4. Description of the nature of the environment (satellite, terrestrial)

4.1 Introduction

In this section, we will attempt to describe the radio frequency environments to which the DARS receiver will be exposed. The most important factors will be explained and quantified. These include some specific propagation aspects and several key channel characteristics. This will lead to a study of the various techniques (modulation, coding, diversity, etc.) that must be used to mitigate the difficult channel conditions created by such environments in order to provide high service availability everywhere inside the target service area. Comparisons of the effectiveness of using these techniques in the frequency bands under study will be made. The emphasis will be put on vehicular reception as being the most demanding and complex reception environment. The use of a geostationary satellite is assumed throughout this study.

4.2 Hybrid satellite/terrestrial operation

An extensive description of the merits and limitations of what has been called the hybrid satellite/terrestrial operation [RAT-90] will be given throughout this report. The general concept behind this hybrid operation is that, although the satellite power is normally set, for practical reasons, to provide adequate service to rural and remote areas, terrestrial repeaters are used to extend the coverage to city and shadowed areas. This will ultimately result in a seamless coverage everywhere inside the target service area for vehicular reception. This hybrid coverage concept has the merit of translating a reasonably achievable predicted probability of coverage into a very high availability of service (e.g., 99%). At the same time, the use of terrestrial repeaters will also provide for this extra power that will allow reception with portable receivers inside buildings. Without terrestrial repeaters, this would only be possible through the use of an excessive power at the satellite (some 20 dB higher power) to compensate building penetration losses especially in areas where the satellite is seen at high elevation angles. The extension of service with terrestrial repeaters can, in fact, be done gradually by installing terrestrial re-transmitters progressively after the satellite has started providing service to the open areas.

The principle of operation of the hybrid concept is that the shadowed areas, especially in built-up environment, can be filled by the excess power that terrestrial repeaters can generate locally at the cost of making the channel multipath environment more difficult. It is based on the fact that new digital modulations have been designed to be able to cope with harsh channel multipath. Using on-channel terrestrial repeaters will produce additional active echoes at the receiver which could be taken advantage of as long as the active echoes generated by the terrestrial repeaters are within a certain excess delay range (i.e., inside the guard interval or inside the equalisation window). As will be seen later, this can be accomplished by proper localisation of the gap-fillers and restricting the power and/or the directivity of these gap-fillers to limit their coverage to a small area, thus ensuring that the satellite coverage, beyond this area, is not affected by the presence of destructive active echoes. With this simple system configuration, normal city coverage can be added to the satellite coverage in an elegant way.

The need and the various merits of the use of terrestrial gap-fillers are further described in Section 4.4.3.

4.3 Propagation aspects

The range of frequencies surveyed in this study for the DARS systems is between 1452 MHz and 2360 MHz. Two frequencies located at the center of the L- and S-bands will be taken to establish the frequency dependency of propagation; that is, 1472 MHz and 2335 MHz.

4.3.1 Free-space propagation and frequency dependency

The dependence of free-space basic transmission loss L_{bf} on frequency f (MHz) is given by

$$L_{bf} = 32.4 + 20\log f + 20\log d$$

where d is the distance in kilometers. The term $20\log f$ is different by **4.0 dB** for the two frequencies of interest and is caused by the reduction of the effective receiving antenna aperture with the increase in frequency. This 4 dB loss can, however, not be recovered by increasing antenna gain because of the need to keep the antenna pattern close to omnidirectional (to avoid the need for a tracking antenna on cars). Although broadcast reception can take place over a large range of heights above the ground, a receiving antenna height of 1.5 m is assumed in this section because this antenna height is appropriate for vehicle reception and that if coverage can be obtained at this height, it can also be obtained higher up.

4.3.2 Satellite propagation aspects

4.3.2.1 Absorption by trees

Depending on the distance between the receiving antenna (assumed close to the ground) and the nearest trees, radio waves may arrive by diffraction over the trees, or by passing through the trees. This section is concerned principally with the absorption of radio waves passing through trees. This is of concern where a roadway is lined by a row of trees, or in a residential area containing mature trees. For short paths through trees, the decay in received power is exponential with the distance d through which the wave must pass through the trees. An expression for this loss, due to Lagrone [LAG-77] is:

$$L = 0.00129 f^{0.77} d$$

An extensive study of the absorption of radio waves by trees in temperate climates was made later by Weissberger [WEI-82]. He quoted Lagrone and others, but proposed the following model based on data taken in a cottonwood forest in Colorado in the frequency range 230 MHz to 95 GHz:

$$L = 0.063 f^{0.284} d \qquad 2 < d < 14\text{m}$$

$$L = 0.187 f^{0.284} d^{0.588} \qquad 14 < d < 400\text{m}$$

The first formula will be applicable in the case of satellite reception. As a specific example, consider a distance of 14 m, and use Weissberger's formula at 1472 MHz and 2335 MHz. The results are 7.0 dB and 8.0 dB. Using Lagrone's formula, the numbers are 5.0 and 7.1 dB. So the difference with frequency is 1 or 2 dB. However, the numbers just given are average values in a stand of trees of the given thickness. The fades resulting from absorption by individual trees will be much greater.

4.3.2.2 Diffraction over rooftops

Diffraction over rooftops can be modeled as a function of building height and spacing by the methods of Maciel et al [MAC-93]. If the elevation angle becomes larger than about 2°, which will be the case for satellite reception, only one roof is expected to obstruct the wave, and we have simply a single knife-edge diffraction loss as explained in Section 4.3.3.1, with a frequency difference of 2 dB.

4.3.3 Terrestrial propagation aspects

4.3.3.1 Knife-edge effects

Many terrain obstructions can be modeled as knife edges, for example buildings, trees, and distinct ridges. The amplitude of the wave field in the shadow of such an object is proportional to the amplitude of the complementary Fresnel Integral F(x), which, well within the shadow region, is approximately given by 1/2x. The value of x, in turn, is proportional to $\sqrt{f}$. This means that received power is proportional to 1/f, and a knife-edge obstruction adds a term 10 log f to the path loss, giving 2.0 dB more received power at 1472 MHz than at 2335 MHz.

4.3.3.2 Diffraction over terrain

Longley-Rice

A widely used site-general model for diffraction over terrain is the Longley-Rice model, or ITS Irregular Terrain Model (in the area prediction mode), the most recent version of which is described by Hufford *et al* [HUF-82]. The terrain is assumed to be generally uncluttered. A parameter to be set is the interdecile height variation Δh of the terrain. Hufford suggests 90m as a representative value, and ITU-R Recommendation 370 [ITU-86a] suggests 50m. The latter value is perhaps more representative of populated areas, and is used here. The results presented below are sample runs at the two frequencies of interest, in which the transmitter is assumed to be carefully sited and the receiver randomly sited. The numbers given are path loss (dB) in excess of free-space loss.

Base station height = 100m Mobile station height = 1.5m Δh = 50m 50% time 50% locations

Distance (km):	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
2335 MHz	4.0	11.1	18.0	24.8	31.4	37.3	43.1	49.1	55.1	59.3 dB
1472 MHz	6.2	12.7	19.0	25.4	31.2	36.5	41.8	47.0	52.4	57.8 dB
difference	**-2.2**	**-1.6**	**-1.0**	**-0.6**	**0.2**	**0.8**	**1.3**	**2.1**	**2.7**	**1.5 dB**

The inference from this model is that the diffraction loss due to uncluttered irregular terrain does not change by more than about 2 dB between the frequencies of interest. The reason for the negative differences at short ranges is presumably that in the physical model used, the first Fresnel ellipsoid is only partly obstructed on the shorter paths, and as the ellipsoid becomes narrower at the higher frequency, it becomes less obstructed.

ITU-R Recommendation 1146

The third model is the entirely empirical model contained in ITU-R Recommendation 1146 [ITU-95a]. In this model, for receiver (or mobile) heights above the clutter, the path loss increases with frequency by values between 0.7 and 1.8 dB. Recommendation 1146 also has a correction for lower antenna heights, which at 1.5m gives, according to the type of clutter:

	Rural	Suburban	Urban/Wooded	Dense Urban
2335 MHz	19.7	27.2	37.5	43.0
1472 MHz	18.6	22.9	31.0	36.5
difference	**1.1**	**4.3**	**6.5**	**6.5**

That is, the attenuation due to the receiving antenna being below the clutter and close to the ground increases with frequency by values between 4.3 and 6.5 dB in built-up or wooded areas.

4.3.4 Diffraction around buildings

In a theoretical estimate, there are two kinds of paths to consider, diffraction over rooftops, and diffraction around vertical walls.

4.3.4.1 Many knife edges

Diffraction over rooftops can be modeled as a function of building height and spacing by the methods of Maciel *et al* [MAC-93]. There are two steps in the process. One is the propagation of the wave from the transmitter over many rooftops, and the other is the subsequent diffraction of the wave down to street level. Taking the diffraction down to street level first, this is just a single-knife-edge calculation, and the variation of excess path loss with frequency is 10 log f, as discussed in section 4.3.3.1. The other step to be considered is propagation over many rooftops. If the wavelength is small compared to the distance, the excess path loss is proportional to -9 log f. As with short paths in the Longley-Rice model, the narrower Fresnel ellipsoid associated with a higher frequency is less obstructed. This almost cancels the variation in the other term, leaving a difference of only 0.2 dB at the two frequencies. On the other hand, if the elevation angle becomes larger than about 2°, the other roofs no longer obstruct the wave, and we have simply a single knife-edge diffraction loss, with a frequency difference of 2 dB, as discussed already. So in this model, the difference in excess path loss between the frequencies of interest can be expected to be between 0.2 and 2 dB.

4.3.4.2 Diffraction around buildings

Diffraction around the corners of buildings is a form of wedge diffraction. The dominant term is a knife-edge diffraction term, and a frequency difference of 2 dB can be expected. Successive diffractions around two corners will give 4 dB, but the amplitude of double-diffracted waves is expected to be low compared to that of reflected waves.

4.3.4.3 Hata's empirical equations

Propagation in urban areas can be modeled empirically as well, and a very popular method of doing this is by using Hata's [HAT-80] equations, which are based on a massive set of measurements by Okumura et al [OKU-68]. In these, the frequency variation is 26.16 log f. When the 20 log f of free-space variation is removed from this, the frequency variation of excess loss is 6.16 log f. At the two frequencies of interest, the difference is 1.23 dB. There is also a frequency term in the mobile antenna-height correction, but at a mobile-antenna height of 1.5m this vanishes. On the other hand, a version of the Hata equation as modified by COST 231 (cited by Doble [DOB-96]) specifically for the frequency range 1500 to 2000 MHz has a frequency variation 33.9 log f leaving 13.9 log f for excess loss. At the two frequencies of interest, the difference is 2.8 dB.

4.3.5 Absorption by trees

This topic was covered in Section 4.3.2.1 above dealing with satellite propagation aspects. The difference in absorption between the two frequencies may be more pronounced in the terrestrial case, due to the lower angles of elevation and consequent longer paths through trees in many cases. For example, if the distance traversed through trees is 100 m, Weissberger's formula predicts losses of 22.2 dB and 25.3 dB for L-band and S-band respectively, or a difference of about 3 dB.

4.3.6 Location variability distribution

In rural areas, for all paths of a given length, the standard deviation σ_L of the location variability distribution may be estimated for $\Delta h/\lambda < 3000$ as

$$\sigma_L = 6 + 0.69\left(\tfrac{\Delta h}{\lambda}\right)^{1/2} - 0.0063\left(\tfrac{\Delta h}{\lambda}\right) \qquad \text{dB}$$

and for $\Delta h/\lambda > 3000$ as $\sigma_L = 25$ dB,

where $\lambda = 300/f$, and f is measured in megahertz, and where Δh is the interdecile height variation in the distance range of 10 to 50 km from the transmitter. This formula is equation (11) of CCIR Report 567-4 [ITU-90d], pointed to by ITU-R Recommendation 529-1[ITU-94]. It comes from Longley [LON-76], and describes mainly the effects of hilly terrain, rather than trees or buildings. For $\Delta h = 50$ m, the argument $\Delta h/\lambda$ is 245 and 389 for the two frequencies of interest. This gives σ_L = 15.26 dB and 17.16 dB for the two frequencies.

In flat urban areas, the standard deviation over a large area may be estimated from Figure 39 of Okumura *et al* [OKU-68]. This represents data for an area 2 km in radius, much smaller than for the last equation. The results are σ_L = 7.05 dB and 8.93 dB for the two frequencies of interest. The same diagram gives a curve for a suburban area and rolling hilly terrain, again for an area 2 km in radius. This curve gives σ_L = 7.68 dB and 9.62 dB for the two frequencies of interest. For both the Longley and Okumura data, the variability is for all paths of a given length, not the variability over a small area.

The location variability is important if it is required to obtain coverage over a large percentage of a service area. For a log-normal distribution, the required margins are as follows:

Percentage locations:	**50%**	**84%**	**90%**	**95%**	**98%**
margin, σ_L = 7.05 dB	0	7.05	9.04	11.6	14.5 dB
margin, σ_L = 8.93 dB	0	8.93	11.45	14.7	18.3 dB
difference for flat urban area (2km)	**0**	**1.9**	**2.4**	**3.1**	**3.8 dB**
margin, σ_L = 7.68 dB	0	7.68	9.85	12.63	15.8 dB
margin, σ_L = 9.62 dB	0	9.62	12.33	15.82	19.8 dB
difference for suburbs, hills (2 km)	**0**	**2**	**2.5**	**3.2**	**4.0 dB**
margin, σ_L = 15.26 dB	0	15.26	19.56	25.10	31.3 dB
margin, σ_L = 17.16 dB	0	17.16	22.00	28.23	35.2 dB
difference for hills (10 - 50 km)	**0**	**1.9**	**2.4**	**3.1**	**3.9 dB**

Note that in this last case, the margins seem very high, but the total margins cited would only be required if a circular coverage area were specified for a single transmitter.

The specific result of interest here is that for 95% coverage at a given distance, the margin required is greater at 2335 MHz than at 1472 MHz by some 3 dB.

4.3.7 Summary of Propagation Aspects

A significant difference between L-band and S-band is the 4 dB higher free-space transmission loss in the latter band, due to the smaller effective receiving antenna aperture. This loss is over and above the losses described below. Other losses which can be expected to be higher at S-band include those from absorption by trees (typically 1 to 2 dB higher in the satellite case and some 3 dB in the terrestrial case) and diffraction over rooftops (up to 2 dB higher, particularly in the satellite case where a single diffraction is likely). In urban areas, formulas based upon the work of Okumura and Hata predict that the excess path loss (versus free space) will be from 1 to 3 dB greater in the higher band. In irregular rural terrain, the predictions of the Longley-Rice model do not clearly favor one over the other. However, the empirical model contained in ITU-R Recommendation 1146 does predict greater losses at S-band in all environments, the differences ranging from 1 dB in rural areas to 6.5 dB in urban and wooded areas for a 1.5 m receiving antenna height. Also of interest is the variability of the received signal levels over large areas, since this has a significant effect on overall coverage. The Okumura models predict higher standard deviations at S-band than L-band in all environments. For example, if 95% coverage is desired at a given distance from the transmitter, it is predicted that about 3 dB higher margin will be required at S-band.

Taking all factors into consideration, one can conclude that approximately 6 dB higher satellite transmitter power may be needed at S-band as compared to L-band and a further 4 dB higher transmit power may be needed in the terrestrial case, for a total of 10 dB for typical receiving situations with 95% coverage availability to cover for the extra fading through trees and the increased variability of the signal.

4.4 Channel characteristics

4.4.1 The satellite channel characteristics

All satellite DARS experiments so far confirm that mobile reception of a satellite service is a sizable challenge. Unlike terrestrial installations, satellites have a much more important limitation in terms of the power they can transmit. It is common practice to set the **power on the satellite** such that it produces a weak signal on the surface of the earth, although sufficient to secure operation of receivers a few dB's above operation threshold when proper receive antennas such as satellite dishes are assumed. In a mobile environment the **receive antenna must be omnidirectional**, small and inexpensive. The expectations in terms of receiver antenna gain cannot exceed 5 to 6 dB in the case of car reception unless a rather complex and expensive antenna providing more directivity and gain is used along with a tracking system. Such a tracking system could only be dispensed with in the case of a satellite close to the local zenith (within the beamwidth of the receive antenna).

As an example, let's consider AMSC, a mobile communications satellite able to support 3200 telephony channels. The AMSC satellite is among the most powerful satellites flown operating in L or S-band and it uses advanced technologies such as a deployable 6 m diameter antenna and a 600 W solid state amplifier. Still, the mobile receiver is expected to be equipped with an antenna providing 9 to 13 dBi gain. In a typical satellite broadcasting system for vehicular reception, the onus will be on the satellite side to provide enough power to compensate for the low antenna gain possible at the receiver due to directivity, size and cost constraints and still allow for some fade margin in the link budget.

The next question is how much **fade margin** must be provided?. How much is needed to ensure adequate reception everywhere within the service contour? Obstruction (or **blockage**) is the first factor to be considered. The severity of the fades caused by obstructions depends on the nature of the obstruction. Blockage is usually caused by trees, buildings, road signs, overpasses, bridges, etc. Successful satellite experiments at L-band have revealed that 2 to 3 dB fade margin is sufficient to provide good reception as long as the receiver is in line-of-sight with the satellite [FOO-96]. Unfortunately, the many obstacles lining the road constantly obstruct the line-of-sight, creating fades in the range of 5 to 20 dB. Fade margins of that magnitude are not practical for a satellite system because of power limitations. The reception is affected by these deep fades and the service availability decreases accordingly. It is therefore accepted that reliable reception from the satellite will be possible only where line-of-sight conditions exist. This is a very limiting condition which does not suit well a digital sound broadcasting service aimed at minimizing system outage in vehicular reception and provide seamless coverage.

The **duration** of the signal fades must also be considered in the case of vehicular reception. Efficient techniques such as time-interleaving exist to compensate for relatively short fades. Errors can then be detected and corrected. However, in suburban and urban areas, the fade duration can exceed the capabilities of typical time interleaving techniques when vehicles have to progress at slow speed. This is even more acute in the case of portable (wearable) receivers (i.e., walkman). The densely built-up urban areas represent the most demanding environment because of the extent of blockage and the variability of the traffic speed which can produce long fade durations.

The **magnitude** of the fade is, in most cases, a function of the elevation angle to the satellite. Typical values of elevation angles for receivers located in the continental USA (CONUS), and pointing at a geostationary satellite range from 55° (latitude = 27°, e.g., Tampa) to 30° (latitude = 47°, e.g., Seattle) or even less depending on the orbital location of the satellite. Goldhirsh and Vogel [GOL-92] have developed an empirical model that predicts that, while driving on a highway or a rural road, 1% of the distance traveled will be characterized by fades greater than 10 dB at 55° and 21 dB at 30°. The dominant sources of shadowing in this case are the roadside tree canopies. The effect of the elevation angle on the magnitude of the fade is significant, 9 dB of difference between 30° and 55°. This leads to the consideration of another major factor: the **type of environment** and terrain in which the receiver is operating. The intensity, occurrence and duration of blockage increase as the receiver moves from an open area to suburban area with more trees and buildings and finally into a dense urban area with high-rise buildings near the street. Once in a dense urban area, some of the fades are so deep (>20 dB) and building height is so large that elevation angle has no significant effect except when it reaches values of the order of 80° and above.

Table 4.1 below illustrates the relationship between some of the factors mentioned above, namely the fade magnitude or depth, the type of environment and the elevation angle. It summarizes the results of a satellite field trial at L-band done in Australia, in 1996 [FOO-96]. A carrier wave signal was transmitted at L-band by a satellite and measurements were carried out in two cities to investigate two different elevation angles, 33° and 51°, values that correspond to the domain of interest for the continental USA. Table 4.1 shows the magnitude of the fades encountered and their respective probability of occurrence by a mobile receiver in various parts of the two cities investigated.

Perth, 33°:	1% locations	5% locations	10% locations
Urban	20	12	7
Suburban	12	5	3
Rural, flat	11	4	2
Rural, forest	15	12	9
Open	2	2	<2
High-rise	>21	20	18
Dense urban	>21	18	16

Canberra, 51°	1% locations	5% locations	10% locations
Urban/Dense suburban	11	7	4
Suburban	8	3	2
Rural, flat	<5	<2	<2
Rural, forest	11	6	4
Open	2	<2	<2
High-rise	>21	12	4
Dense urban	20	6	3

Table 4.1: Signal fade depths (dB) as a function of the type of environment and elevation angle (light fading indicates values greater than 5 dB)

For these kinds of considerations (i.e. blockage, elevation angle, environment type), the carrier **frequency** has a relativity minor impact on the actual depth of fade (see Section 4.3.2.2). However, in the unlikely case of a satellite system that would have enough fade margin (i.e., 15 dB) to partially compensate signal blockage, the signal **bandwidth** would then become a factor, particularly in areas where multipath components are nearly as strong as the direct signal (if any). This situation is found in some parts of the urban and suburban areas where large buildings create reflections that are picked up by the omnidirectional receive antenna and make the main signal collapse each time they are out of phase. The magnitude of the fades due to multipath can be reduced by increasing the signal bandwidth. Flat fading progressively turns into selective fading while the bandwidth of the channel increases. In such cases, only selected portions of the bandwidth will collapse while the others will be strengthened by the presence of the multipath energy, making it recoverable. More discussions on the various fading modes can be found in Section 4.5.

Another important factor that must be considered when designing a service to mobile receivers is the **Doppler** effect. This manifests itself as an apparent shift (or spreading, in the case of multipath) of the transmit frequency as seen by the receiver in motion. The shift increases linearly with the speed of the vehicle and with the carrier frequency.

When there is a single main signal component received, the shift is easily tracked by the receiver AFC and the reception is not affected. When significant multipath is present , the various signal components can be shifted in frequency, in opposite directions, and result in "Doppler spreading". This condition is characterized by an arbitrary displacement (or spreading) in frequency of the signal components for which the receiver AFC cannot do much. This will be studied more thoroughly in Section 4.5.

4.4.2 Simplified channel models

Two channel models are often used to describe typical satellite and terrestrial broadcasting channels. Since they will often be referred to in this report, a definition is provided here:

Rician channel: One dominant incoming wave (line-of-sight or a strong reflection) accompanied by some weaker multipath components. A typical example is a terrestrial radio reception on a rural road. This model is also widely accepted as representative of satellite reception.

Rayleigh channel: Several multipath components of approximately equal amplitude, no dominant component because there is no consistent line-of-sight reception. Typical example: radio reception in a dense urban environment.

It is now possible to examine the channel conditions prevailing in various **types of environments.** To simplify the discussion, only three types of environments will be examined: the **urban** area, the **suburban** area and the **open rural** area.

Let's assume a single-carrier-per-channel (SCPC) satellite service received by a vehicle going from a rural community towards the downtown area of a large city. In the rural area, the impulse response of the channel can be depicted by a single pulse whose amplitude fluctuates from a maximum level (line-of-sight) to practically zero when some obstruction is encountered along the road. The antenna has some gain towards the satellite and reduced gain toward horizon resulting in a reduction of the multipath components from nearby reflecting surfaces. Since the vehicle is moving, the received signal frequency appears to be higher (or lower, depending on the direction of the vehicle relative to the satellite) than that transmitted by the satellite, due to the Doppler shift described above. In this case, since the signal will be received at a given elevation angle from the satellite, the Doppler shift will appear reduced by a factor of ($\cos \theta$). At very low elevation angles, the Doppler shift would be very similar to the terrestrial case whereas for a satellite at Zenith, there would not be any Doppler shift ($\cos 90° = 0$)

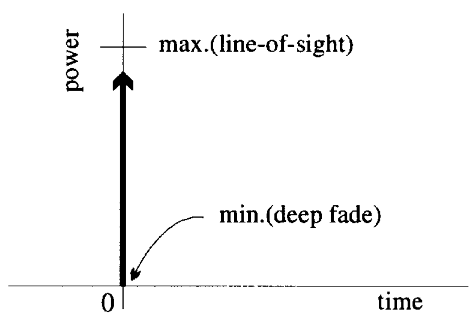

Figure 4.1: Simplified impulse response of a rural open channel.

As the vehicle approaches the more densely built-up area, fade occurrences on the direct path and their duration increase. The service availability begins to decrease and the service interruptions become noticeable. The channel impulse response consists in a large pulse representing the signal received from the satellite followed by a trail of progressively smaller pulses which represent the reflected signals from nearby surfaces, arriving shortly after the main signal, but with much less strength. As the vehicle approaches the city environment, the number, the depth and the duration of the fades on the main pulse will increase due to increased blockage whereas the number and the size of the following smaller pulses will increase due to the number of reflecting surfaces in the neighborhood (see Figure 4.2).

In the case where the satellite transmission only allows for a small fade margin, these later reflections will be lost in the thermal noise of the receiver and will be a negligible cause in the system failure (the main cause being the fading of the line-of-sight satellite signal). However, if the link margin is large enough, these reflections will start to create fading (which may be flat or frequency selective, depending upon the signal bandwidth and the excess delay of the echoes) since the noise floor of the receiver will be comparatively lower. In general, in order to keep the required satellite power within a reasonable limit, the first case described above is a more reasonable assumption.

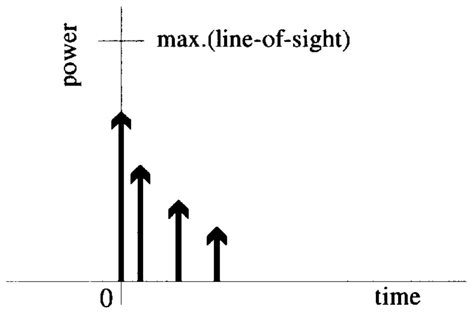

Figure 4.2: Simplified impulse response of a suburban channel.

Now let's assume that the receiver has reached the downtown area. Line-of-sight reception will be feasible at a reduced percentage of locations such as intersections, parking areas and streets parallel to the satellite's azimuth. Blockage from buildings will cause deep fades and the reflected signals will usually be too weak or too unstable to be of any use. The vehicle speed will be variable and, at times, very slow resulting in relatively long fades, rendering time-interleaving in the modulation less effective.

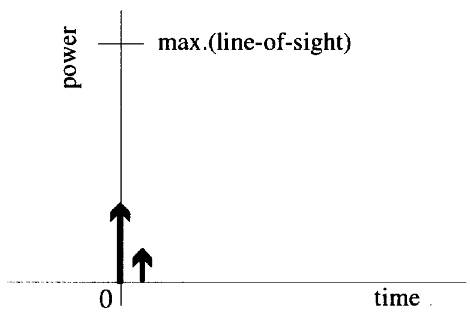

Figure 4.3: Simplified impulse response of an urban channel.

4.4.3 The need for gap-fillers

Our investigation so far has shown that limitations in satellite power will cause service interruptions in certain areas within the service contours. This is the case for areas where constant blockage is present due to terrain features, trees, buildings and other man-made structures. Due to the frequencies considered, the extra power required at the satellite to provide the required fade margin would be beyond practical limits. This is why another means has to be found to cover these shadowed areas. The deployment of on-channel terrestrial repeaters is considered to be the only effective way to provide **seamless coverage** for vehicular reception. This is the only way to locally supplement,with extra power, the satellite coverage in those areas where the fade margin would need to be much higher to compensate for blockage.

Even using space diversity at the satellites (e.g., 2 geostationary satellites on largely separated orbital positions as proposed by two DARS system proponents) can only partially mitigate such blockage since both would be received with minimal fade margins, producing two signals close to the receiver threshold, hence still resulting in minimal margin to combat blockage. The principle of using two geostationary satellites in this case is to decorrelate the fading on both paths so that the resulting availability is increased. This is expected to be beneficial in rural environment and on highways where a reasonably high availability is already possible (e.g., 90% availability on each path would translate, at best, into 99% overall availability if the two paths were to be totally decorrelated, a likely example is the elimination of system drop-outs caused by road signs). Fade correlation would be minimized through maximizing the orbital separation between the two satellites within the practical limits of the geometry since this would tend to translate into lower elevation angles from the satellites, thus more blockage). In an urban environment, the improvement in service availability is likely to be much constrained since the availability on each path will be much lower and the correlation of the fades on the two satellite paths is likely to be much greater; the worse case being a full fade correlation which would not provide any improvement over the single satellite case.

Furthermore, depending on where the receiver would be located and the geometry of the satellite transmit paths, the difference in delay between the two signal paths may be quite extensive, therefore creating other problems at the receiver, similar but more extensive than those that will be reported later relating to the size of the time-domain equalization window in the case of a single carrier modulation, and the extent of the guard interval in the case of a multi-carrier modulation.

The only way to effectively compensate for urban blockage is by being able to locally produce a large excess power to allow reflected paths with still high enough signal strength to reach the receiver to cover areas that cannot normally be reached through line of sight. This can only be done through the use of **terrestrial repeaters**.

This is a form of **space diversity** which provides the receiver with new sources of signal for the same service. Typically, the polarization used for satellite transmission is circular to remove the effect that Faraday rotation would have on tilting the linear polarization as well as the effect of the geometry which would make the polarization tilt different in different geographical areas. However, vertical polarization would likely be used for terrestrial transmission for convenience in the receive antennas on cars and portable receivers as well as ease of implementation at the transmitter. The use of such space diversity at the transmit end (i.e., satellite plus terrestrial repeaters)implies that the receiver will need to be equipped with a high quality circularly polarized antenna with maximum gain towards the elevation angle of the satellite and some form of vertically polarized receiving elements with some gain towards the horizon for receiving signals from the terrestrial transmitters.

The terrestrial transmitters could use a different frequency than the satellite transmission to supplement the satellite coverage but then the receiver would have to contend with two RF front ends tracking the level of the signals and switching to the one with the highest strength. This would also result in the use of more frequencies for the same service, and thus less efficient use of the spectrum. On the other hand, if the same frequency is used, the terrestrial signal would be received as an echo of the satellite signal. This "active" echo would typically render the multipath environment more severe wherever both the satellite signal and the repeater signal are received and even more so where several active echoes from several terrestrial on-channel repeaters are receivable. The resulting condition is rather complex and very similar to the case of multi-transmitter coverage in the terrestrial case as described in detail in the ITU-R Special Publication on DSB [ITU-95]. It is felt that a more detailed description of this situation in the case of a hybrid satellite-terrestrial coverage is warranted in the current context.

4.4.4 Satellite and terrestrial repeaters

The path geometry involved for a satellite coverage supplemented by terrestrial repeaters is illustrated in Figure 4.4. At first glance, it appears that with this simple system configuration, normal city coverage can be added to the satellite coverage in an elegant way without any drawback. It can be observed that, from the point of view of the receiver, the two signal components arrive at different times and the delay between the two signals increases as a function of the distance from the terrestrial repeater. The channel impulse response at the receiver input depicted in Figure 4.4 shows the delays and relative signal strengths as the vehicle moves away from the repeater.

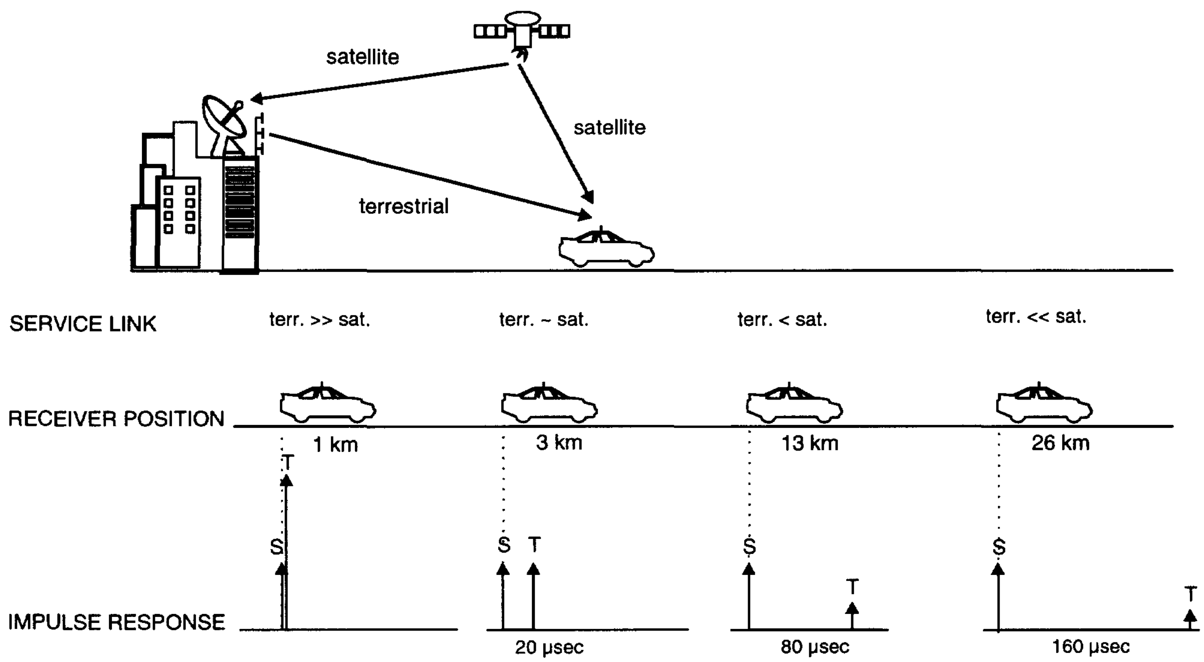

Figure 4.4: Path geometry and related active echo position in a hybrid satellite/terrestrial service

The addition of the "active echo" from the terrestrial repeater has a major impact on the channel conditions. The resulting channel impulse response is characterized by the presence of a strong multipath component that has a delay value exceeding by far the typical delay spread values found in any other multipath environments. Limiting again the discussion to three types of environments, we can examine more closely the impulse response in the urban area, the suburban area and the open rural area. Also, for the moment, it is assumed that only one terrestrial repeater is employed for terrestrial augmentation. The repeater receives the satellite signal (circular polarization is assumed) and simply retransmits it after some filtering and amplification, using a vertically polarized transmit antenna. No frequency conversion is done. This means that the receiver does not have to look for the complementary signal on a different frequency. It is a transparent process.

Another aspect to keep in mind at this stage is that the receiver expected to operate in a hybrid satellite/terrestrial service environment could be equipped with either a special dual antenna/front-end sub-system that can detect the presence of a terrestrial signal and switch from the circularly polarized satellite antenna to the linearly polarized terrestrial antenna or it could be equipped with a compound antenna which has maximum circularly polarized gain at the elevation at which the satellite is seen (e.g., 5 dBic) as well as some vertical gain towards the horizon (e.g., 0 dBi), the signal from these two receive antenna sub-systems being added passively. For simplicity sake, the second implementation is preferred in the following analysis. A simple circularly polarized antenna, optimized for satellite reception, with elevation angles ranging from 30 to 55 degrees with an additional vertical monopole for terrestrial reception is assumed hereafter.

Back to the case study: a SCPC satellite service is received by a vehicle going from a rural community towards the downtown area of a large city. In the rural area, it can be assumed that the channel environment is the same as that of the situation described above (i.e. satellite alone, no terrestrial repeater being used) except that for some parts of the coverage area the signal emitted by the terrestrial repeater will be present, probably very weak due to the long distance to the transmitter. At places where the terrestrial signal is useable, (probably near the suburban area), the resulting channel is characterized by a strong satellite signal accompanied by a weak terrestrial signal with some excess delay (see Figure 4.5). The delay value depends on the geometry of the links between the receiver, the satellite and the terrestrial repeater. The largest excess delays are encountered when the vehicle is moving in the direction of the satellite with respect to the repeater. On the opposite side of the repeater, the excess delay values are much shorter since both signals have traveled more or less the same path. This shows that the receiver will have to cope with a non-negligible multipath component that can have excess delay values ranging from short to extremely long. Again, the zone affected by the presence of both signals is limited to areas where the terrestrial signal has sufficient strength to overcome the path loss and the discrimination (gain and polarization) from the receiver antenna. In short, the zone affected will depend on the emitted power of the terrestrial repeater.

The channel for this particular environment can be depicted by a single impulse whose amplitude fluctuates from a maximum level (line-of-sight) to practically zero when some obstruction is encountered along the road. The passive multipath ("passive echoes" due to reflection surfaces around the receiver antenna) will typically be negligible since it will be below the noise threshold of the receiver due to the relatively small operation margin of the satellite system. As seen before, this channel behavior is representative of the Rician model. This single impulse is shifted in frequency by the Doppler shift, upward if the vehicle moves towards the satellite and downward if the vehicle moves in the opposite direction with respect to the terrestrial repeaters. Then, with the addition of a terrestrial on-channel repeater, a second impulse is added to the channel impulse response representing the signal received from this repeater. The relative amplitude of this pulse varies according to the physical distance to the repeater, and to the amount of blockage present (log-normal model).

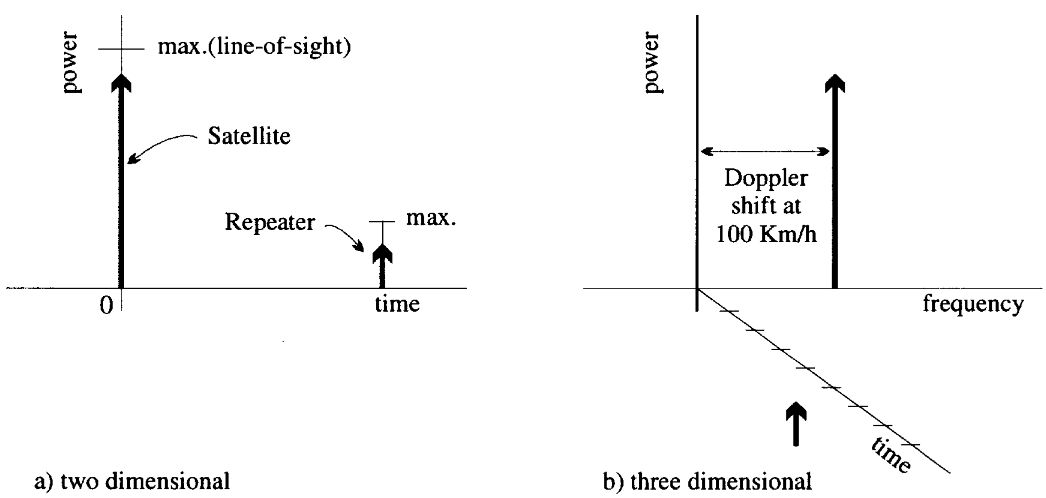

Figure 4.5: Simplified impulse response of a rural open channel, hybrid satellite/terrestrial service.

As the vehicle approaches the suburban area, the satellite signal fades more frequently due to blockage by buildings and trees. The terrestrial signal starts being useable to fill these service holes but it has just enough fade margin to meet the requirements in the suburb area. The non-desired effect of the presence of the terrestrial signal is that it creates a severe multipath environment at all locations where both the satellite signal and the terrestrial signals are received at a useable level. The active echo generated by the terrestrial repeater has a long delay exceeding typical suburban delay spread values in a portion of the coverage area (see Figure 4.6a) . Its Doppler shift will typically exceed that of the satellite signal because of the low elevation angle to the terrestrial transmitter (Doppler shift is proportional to the cosine of the elevation angle of arrival of the signal). Furthermore, there will be passive echoes from the repeater in a terrestrial environment which will be received at various amplitudes, typically according to the Rayleigh model in an urban/suburban environment (see Figure 4.5a). In addition, depending on the direction of the vehicle displacement relative to the repeater and angle of arrival of these passive echoes, these pulses will be shifted in frequency upward and downward (see Figure 4.5b). This is what creates the Doppler spread effect at the receiver which cannot be compensated by the receiver AFC since the shifts are in different directions. The channel can be characterized as a mixture of Rician and Rayleigh channel conditions (see Figure 3.6b).

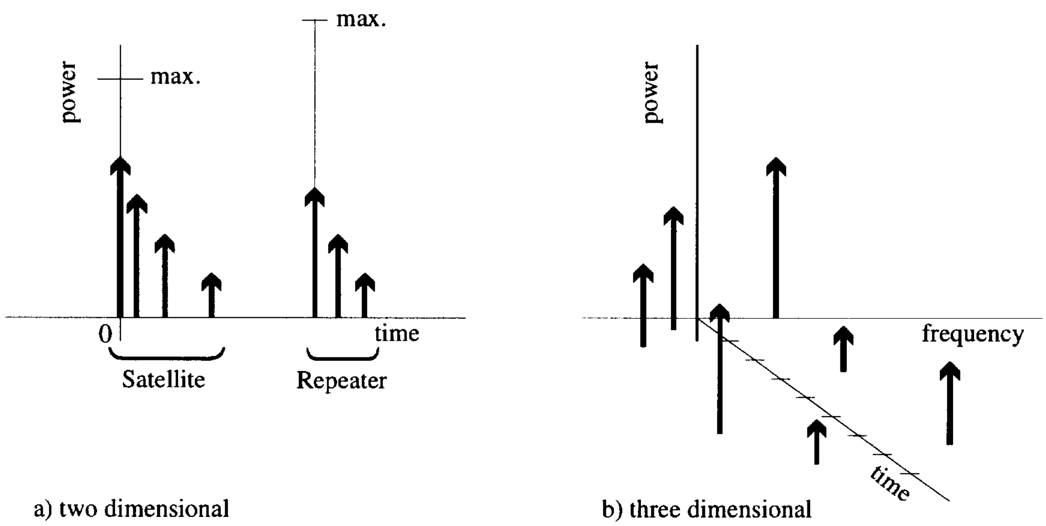

Figure 4.6: Simplified impulse response of a suburban channel, hybrid satellite/terrestrial service.

When reaching the downtown area, the dominant signal is received from the terrestrial repeater. In principle, it has sufficient fade margin to adequately cover the neighboring area by itself whether the vehicle is moving or stopped. Blockage from buildings causes deep fades for both direct signals but the reflected waves from the repeater signal are strong enough to be used by the receiver and compensate for the fades on the direct signal path (see Figure 4.7a). Their phase is random and so is the Doppler shift. The vehicle speed is low and the Doppler effect is small when compared to the rural environment. This situation is well represented by a Rayleigh channel model (see Figure 4.7b).

Figure 4.8 summarizes this discussion in a graphical way. This illustration also reveals the relative size of the areas affected or characterized by the three different channel models.

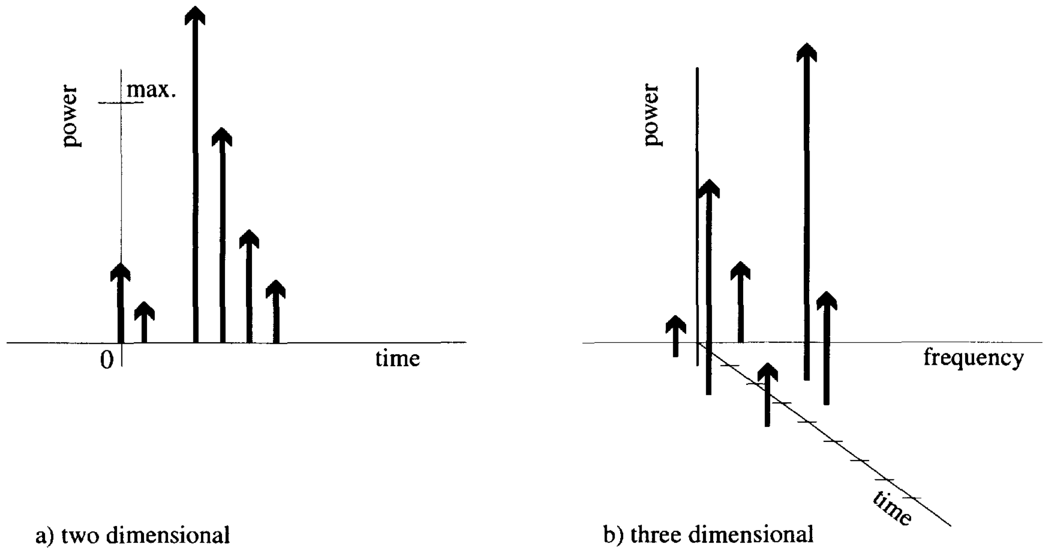

Figure 4.7: Simplified impulse response of an urban channel, hybrid satellite/terrestrial service.

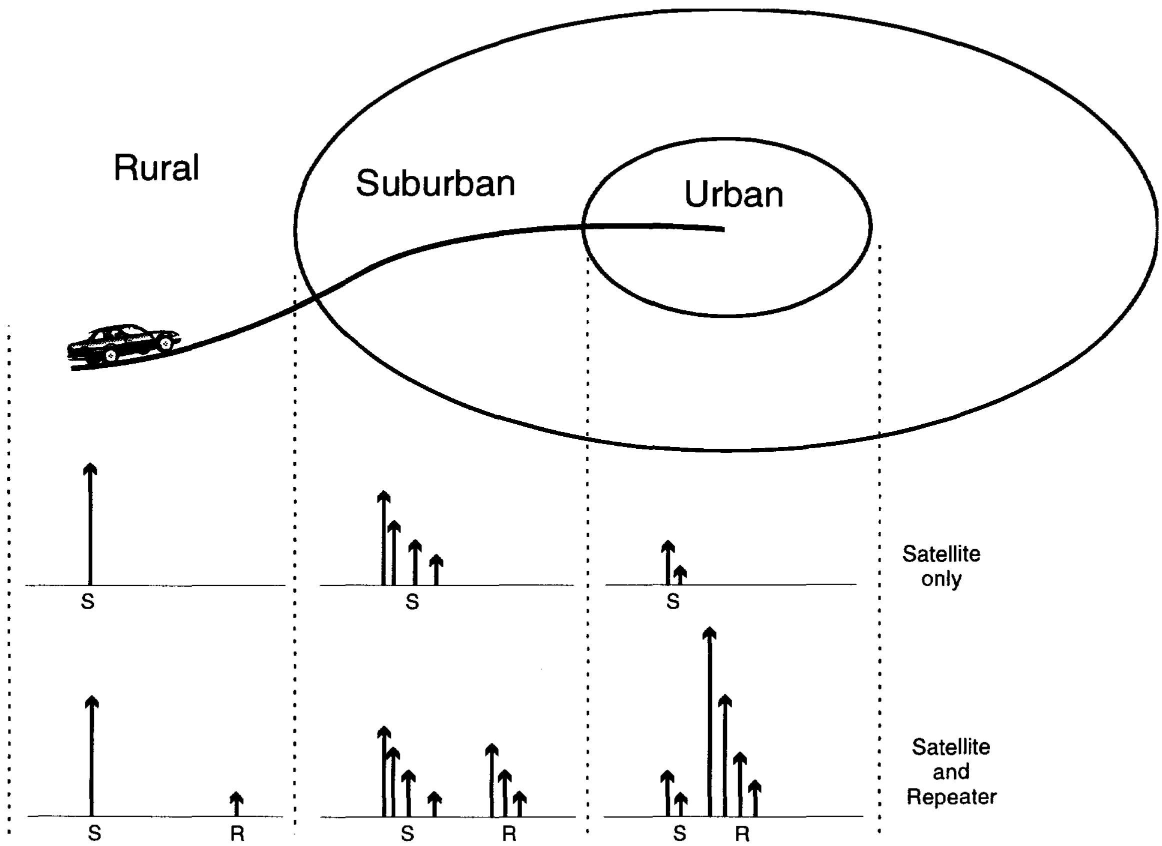

Figure 4.8: Impulse responses in the three types of environment

4.5 Mitigation techniques to counter transmission channel impairments

In Section 4.4.2, it was made clear that the mobile environment is characterized by the presence of large fades and strong multipath signal components. If no mitigation technique is employed, this results in frequent service interruptions due to flat fading of the signal (shadowing, normally modeled by a Log-normal statistical distribution) and frequency selective fading (multipath, modeled by a Rayleigh statistical distribution). These two fading conditions must be treated separately as they require different solutions.

4.5.1 Case of a flat fading channel

Flat fading is a condition where the whole signal bandwidth is equally faded. An example of flat fading is the effect on the reception of an obstruction created by a large building along the street. During the fading period, the information is lost. Typically, bit error correction techniques allow the receiver to reconstruct this information, or part of it, as long as the fade does not exceed the time interleaving depth implemented in the channel coding. If it exceeds this maximum time such as in the case of a car stopped at a red light, there is nothing that can be done to recover the signal except through space diversity. In this case of blockage, receive antenna diversity would not help much since the area of blockage is likely to be larger than the spacing that can be achieved between multiple receive antennas mounted on a car. Space diversity at the transmitter is thus necessary and this is the reason for the need of on-channel repeaters to try to produce seamless coverage even in obstructed environments. The local terrestrial repeater will be able to produce enough excess power to allow reflections to reach the receiver with high enough strength to allow reception even though the direct paths are obstructed.

4.5.2 Case of a selective fading channel (multipath)

Frequency selective fading is caused by the presence of strong reflected signals which create a very complex standing wave pattern through which a car has to go. Since the repetition cycle of the signal is in the order of the wavelength, the channel variability created through the motion of the car can be very high. This is the time domain explanation of a Rayleigh frequency selective channel which suffers Doppler spread. In the frequency domain, this condition creates nulls at specific frequencies in the signal bandwidth and the channel is therefore considered frequency selective. The location of these nulls vary with time due to the displacement of the vehicle. This variation can be very fast depending on the speed of the vehicle. At low vehicle speed, the tracking of the channel conditions is rather easy even though time interleaving becomes less effective. Well optimized modulations will be able to recover the signal properly in this case except in the presence of a high amplitude close-in reflection. In such case, if the reflection is close enough, a flat fading will occur at the receiver and, if the vehicle does not move fast enough, time interleaving, as explained above will not be able to compensate for this fade. An example of this occurs when a vehicle is brought to a standstill at a stop sign. Even though the physical distance to cover to get out of this flat fading is small, typically in the order of the wavelength (13-20 cm), this can occur for a certain time, exceeding the time interleaving depth of the modulation. The condition for such a flat fade to occur is related to the coherence bandwidth of the channel which is directly related to the excess delay of the reflection by the following simplified formula:

$$T \approx 1/BW$$

Several field measurements have been conducted to characterize multipath at UHF from a single terrestrial transmitter. In [KAH-94] for instance, 80% of all the delay spreads measured at 1.5 GHz in a wide variety of areas (rural, suburban, urban, dense urban, wooded) had a value smaller than

5.14 μsec. In measurements made at 900 MHz in four US cities [RAP-90], the delay spread was smaller than 5 μsec approximately 78% of the time, which is in good agreement with the measurements at 1.5 GHz in [KAH-94]. Measurements made in London, UK at 900 MHz [GUR-87] over two 1 km runs showed that nearly 100% of the delay spread values measured were less than 5 μsec. In typical sectors of a hilly area, measured delay spreads were less than 5 μsec 85% of the time while this value increased to 9 μsec over "bad" sectors [GUR-87]. Although the measurements reported here were made at 900 MHz and 1.5 GHz, it is reasonable to assume that they would hold true at 2.3 GHz as well. These field measurements show that radio channels with coherence bandwidth of 200 kHz or more occur quite frequently in non-hilly environments.

As an example, a 200 kHz bandwidth signal can experience flat fading with any high amplitude echo with excess delay of less than approximately 5 μsec whereas a 1.5 MHz bandwidth signal can experience such flat fading for echoes with excess delay of approximately 0.67 μsec. Most high amplitude echoes typically fall in the 1 to 6 μsec range in the urban and suburban cases; this is the reason why a wide bandwidth DAR system has a clear advantage in terms of signal robustness in these environments. Studies looking at the impact of signal bandwidth on received signal levels at L-band have shown that an *optimum* signal bandwidth seems to be around ***2 MHz***. [ITU-91a]. In the case of such a flat fading, there are, however, other means to alleviate the problem. Time diversity will be effective if the car is in motion, creating a time varying channel. However, if the car is stopped, space diversity has to be used, either at the receiver with receive antenna diversity or at the transmit end with on-channel repeaters.

At high vehicular speed, time interleaving would help to average the errors but the channel conditions vary so much that a large amount of errors is constantly produced due to the receiver not being able to track the highly varying channel conditions. There is no means to alleviate such condition except by the presence of a much stronger signal from a local repeater (creating an artificial local Rician channel condition) which would allow the receiver to lock with its AFC, discarding the much lower multipath components which make the channel too complex to be decoded. This hard limit for which, unlike in the previous channel conditions, there is no other diversity means, is the reason for the **intrinsic limit in carrier frequency for mobile reception** in a complex environment. The consequences of this, especially in the context of a satellite service complemented by terrestrial on-channel repeaters will be explained in the following sections.

4.5.3 Existing technologies to counter transmission channel impairments

The channel conditions prevailing in a mobile reception environment were described in Section 4.4.2 and 4.5.1. With the recent advances in DSP technology, a variety of techniques previously considered as theoretical and impractical are now feasible. This makes it possible to devise powerful error detection and correction methods, robust digital modulation and adaptive mitigation techniques such as channel estimation and equalization as well as the use of multi-carrier modulation.

There are a number of mitigation techniques, as seen above, to correct for the harsh environment resulting from mobile reception: time diversity (time interleaving), frequency diversity (frequency interleaving) and space diversity (receive antenna space diversity and transmit antenna space diversity). These tools are available to combat the various channel conditions but the price to pay for the resulting robustness is usually in the form of a loss of channel capacity, increased complexity and processing delays and receiver complexity, as well as increased power consumption at the receiver. The best system is therefore the one that allows the best set of trade-offs among these various aspects.

5. Multi-carrier modulation (COFDM)

One of the main candidate modulations for DAR systems is the Coded Orthogonal Frequency Division Multiplex (COFDM) modulation as used in the Eureka-147 DAB system [ETS-95].

5.1 System description

In digital transmission, the performance of the system is determined by the capability of the channel coding and modulation to adapt to the impairments of the transmission channel. This section will describe the channel coding and modulation scheme employed in a multi-carrier modulation to work in a satellite as well as terrestrial environment. As reviewed in detail in Section 4, for the specific application of satellite DARS (L- or S-band) with complementary terrestrial on-channel repeaters aimed at producing seamless mobile reception, the most problematic channel impairment is certainly fading due to shadowing and multipath. In a frequency-selective fading situation, where only a portion of the signal spectrum is faded, the conventional approach associated with single carrier modulation is to consider a form of signal ***equalization*** to reduce the inter-symbol interference (ISI) that results. This will be explained further in Section 6.

A very effective approach to dealing with frequency-selective fading is to segment the signal bandwidth into N carriers, such that each is flat faded, and then separate the data stream into N sub-streams, each assigned to a carrier and having a symbol period N time longer. The objective is to:

- transparently survive the loss of a certain percentage of narrow carriers in the channel;
- minimize inter-symbol interference.

This approach is referred to as multi-carrier modulation, with a very specific implementation known as Orthogonal Frequency Division Multiplexing (OFDM).

The merits of multi-carrier OFDM are examined next.

5.1.1 OFDM

As mentioned previously, by segmenting a frequency-selective faded channel in the frequency domain into N orthogonal carriers - orthogonal frequency division multiplexing - it is possible to have multiple flat faded carriers, where some are flat faded some of the time, but never all of them. When used with proper coding and interleaving, it is possible to achieve a system that can be decoded correctly even when a certain percentage of the carriers is completely lost due to flat fading. This is an effective way to provide frequency diversity where some frequency selective fading is experienced in the transmission channel and time interleaving cannot help because the vehicle is moving at a relatively slow speed.

As well, the data stream is separated into N sub-streams, each assigned to a carrier and having a symbol period N times larger and a data rate N times smaller. This leads to a reduction in multipath ISI. Such ISI can actually be totally removed with the use of a guard interval in the transmission during which the receiver ignores the signal from the channel (see discussion of *guard interval* below) as long as all the echoes that fall within this guard interval.

The design objective is to achieve a sub-channel bandwidth that guarantees flat fading while at the same time stretching the symbol period so that it is much longer than typical echo delays. Both of these objectives are achieved by selecting a value of N sufficiently large. This segmentation of the data into sub-channels is performed with an inverse Fast Fourier Transform (FFT) at the transmitter and the recovery of the data is done through a FFT chip in the receiver.

If the system is properly designed and the numbers for sub-channels and their individual bandwidths are properly selected, the individual sub-channels will suffer from flat fading. ***Interleaving in the frequency domain*** using a pseudo-random sequence will ensure that flat fades in successive sub-channels will not correspond to loss of successive data symbols; this provides for randomization of the errors caused by multipath fading. ***Error randomization*** is important because channel decoders (using the Viterbi decoding algorithm) in the receivers are better able to handle randomly distributed errors than clustered errors. Reordering symbol errors so that the decoder perceives them as independent maximizes the decoding efficiency. Likewise, ***interleaving in the time domain*** using a similar pseudo-random sequence ensures that time-domain impairments will not correspond to loss of successive data symbols; this further ensures error randomization.

Without appropriate ***coding*** that provides adequate recovery from lost symbols after de-interleaving in time and frequency, the advantage of OFDM could not be retained. Coding in conjunction with frequency and time interleaving provides a link between bits transmitted on separate carriers of the signal spectrum, in such a way that information conveyed by faded carriers can be reconstructed in the receiver using coding links relating them to information from undamaged carriers.

Coding and interleaving applied to OFDM can be considered as a method of averaging local fades over the whole signal bandwidths and over the time interleaving depth. It is important to recognize that coding and interleaving are essential characteristics of any digital transmission scheme, not limited to the OFDM approach.

If a constant amplitude constellation (i.e., *m*-PSK, QPSK, DQPSK, etc.) is used, there is no need to equalize the individual sub-channels, because the signal phase (not the signal amplitude) carries the information. Furthermore, if a differential encoding approach (i.e., DQPSK) is used, phase reference information to help the receiver synchronize is not necessary, as the phase difference between successive symbols contains the information. For these reasons, ***DQPSK*** modulation is the preferred modulation for broadcasting services targeted to mobile reception. In the case of a satellite only broadcast system, coherent demodulation would be preferred since it allows a reduction of 3 dB in satellite power. However, if a hybrid approach is to be implemented with terrestrial repeaters used to complement the satellite coverage in shadowed areas, differential modulation will have to be used since excessive overhead would be required to train the receiver in a terrestrial mobile context (Rayleigh channel).

In order to further minimize the impact of ISI due to multipath fading, a buffer is inserted between successive time symbols. Referred to as the ***guard interval***, this buffer typically has a time duration equal to 20% of the total transmitted symbol. This is equivalent to a 1 dB power loss in the transmission, but the resulting gain from ISI elimination, especially in very difficult multipath environments is compensated many-fold. At the receiver, the signal energy occurring during this buffer period is ignored, and all energy occurring within the useful symbol period is considered as constructive energy.

The COFDM system with interleaving and guard interval is designed to be robust in a multipath environment where naturally occurring echoes exist. It is able to handle any echoes of any amplitude and time delays within the guard interval. This characteristic can be taken advantage of by creating active echoes, in this context with ***on-channel repeaters***, to act as gap-fillers, coverage extenders or as part of a synchronized or non-synchronized single frequency network (SFN) in the case of terrestrial DAR broadcasting as described in the ITU-R Special Publication on DSB [ITU-95b]. The distance between transmitters must respect the condition that signal propagation time must not exceed the guard interval, otherwise the receiver will see some of the signals falling outside the guard interval and they will start producing ISI.

As examples of COFDM configurations with signal bandwidth, number of carriers and guard interval duration, Table 5.1 presents the four possible modes of operation of the Eureka 147 DAB system described in reference [ETS-95].

	Mode I	Mode IV	Mode II	Mode III
Number of carriers	1536	768	384	192
Carrier spacing [kHz]	1	2	4	8
Useful symbol duration [μs]	1000	500	250	125
Guard interval duration [μs]	246	123	62.5	31.25
Signal bandwidth [kHz]	1536			
Modulation	DQPSK			
Raw data capacity [kbit/s]	2304			
Useful data capacity [kbit/s]	1152 (with rate ½ error correction coding)			

Table 5.1: Transmission Modes for the COFDM portion of the EUREKA-147 system

The carrier spacing will determine the impact of Doppler spread interference, but this is also a function of operating frequency and vehicle speed. The impact of the Doppler spread sets the upper limit for the selection of the value of N: too large a value will result in unnecessary performance reduction due to Doppler interference. In fact, a very basic trade-off in the context of the COFDM modulation is the sensitivity to Doppler spread versus the extent of the guard interval. Typically, the longer the guard interval is, the larger the separation between terrestrial repeaters can be. The number of these repeaters to cover a given area will be related to the size in the guard interval as a square function. This is the reason why the guard interval needs to be stretched as much as possible within the constraints of the Doppler spread. Also, it was found that for a given percentage of guard-interval versus total symbol period, the maximum speed of a vehicle allowed before the Doppler spread starts to affect the quality of the reception is linearly related to the carrier frequency.

In order to allow the system to operate properly at 2.3 GHz, the speed of the vehicle would have to be reduced by a factor of 0.6 with respect to the speed allowed at 1.5 GHz. Another way would be to reduce the symbol duration by a factor of 0.6 so that the faster channel transitions due to the increased Doppler spread at this higher carrier frequency can be accommodated with an equivalent system performance. This would allow a smaller number of carriers and consequently, a larger carrier spacing. If the same relationship is kept between guard interval and symbol period in order to keep the same channel throughput, the guard interval would therefore be reduced by a factor of 0.6. In a terrestrial coverage case, this would mean an increased density of repeaters of $(1/0.6)^2 = 2.8$ when consideration of propagation is neglected.

Yet another approach would be to favor an increase of signal bandwidth to maintain the same throughput and Doppler performance with an optimal repeater density. In this situation the first constraining factor is the symbol duration which must be kept short to avoid Doppler spread effects. The guard interval can be adjusted to a larger percentage of the symbol duration to keep the same repeater spacing. This has the effect of reducing the channel capacity but it can be compensated by an increase of channel bandwidth. For example, if the symbol duration is reduced by a factor of 0.6, the guard interval/symbol ratio is increased from 20% to 30%, and the carrier spacing is enlarged by a factor of 1.66 (i.e. 1/0.6). This arrangement yields, at 2.3 GHz, an equivalent data throughput and an equivalent robustness to Doppler spread, as experienced with Mode II at L-band, but note that the signal bandwidth had to be increased from 1536 kHz to 1740 kHz.

The effect of frequency scaling in the case of satellite coverage augmented by terrestrial repeaters will be covered in Section 5.2.

5.1.2 COFDM and satellite transmission

Studies were carried out on the transmission of COFDM in a non-linear transponder typical of satellite transmission. It was found that in order to keep the sidelobes down to 20 dB, the transponder has to be operated at 2.0 dB output back-off in the case of COFDM compared to 0.3 dB output back-off for a single carrier constant envelope modulation. At an output back-off of 2 dB, the required Eb/No value for COFDM at the receiver to maintain a BER of 10^{-4} is only 1 dB higher than in the case of an ideal linear amplifier [LE-95]. This result was found for both a TWTA and a SSPA. This demonstrates that meeting the sidelobe rejection level is more constraining than the in-band error generation. There is therefore some cost at using COFDM over satellite but this is amply compensated in the case of a hybrid satellite/terrestrial by the fact that a common modulation scheme can be used for both satellite and terrestrial transmission to produce seamless coverage. Although coherent demodulation is the preferred choice to minimize the satellite transponder power requirement, differential modulation would need to be used in a hybrid operation to cover for the mobile reception from the terrestrial repeaters.

5.2 Coverage case study for multi-carrier modulation

This section looks at the coverage impact of using terrestrial on-channel repeaters to complement mobile reception of satellite transmission of a multi-carrier modulation using the Eureka 147 DAB system as a model, operating in Transmission Modes II and IV at L-band and a new Mode IV scaled according to the carrier frequency at S-band for the purpose of the comparison.

Assumptions:

- ITU-R Recommendation 370 propagation model with 50 m terrain roughness factor for rural reception; equivalent to FCC propagation curves [ITU-86a]; including scaling of the propagation prediction in terms of receive antenna height (1.5 m rather than 10 m) and it terms of frequency [ITU-91b];
- Okumura-Hata fading model [HAT-80] for urban reception;
- satellite downlink budget similar to that presented in the ITU-R Special Publication on DSB [ITU-95b];
- satellite fade allowance of 5 dB;
- signal availability for 95% of locations based on log-normal distribution with 3.9 dB standard deviation for satellite and 5 dB for terrestrial;
- omnidirectional receive antenna at 1.5 m height AGL with 5 dBic satellite gain and 0 dBi terrestrial gain;
- minimum required C/(N+I) = 10.4 dB for a BER of 10^{-4}, including allowance for Doppler spread, hardware implementation, satellite uplink degradation and interference;
- receiver noise figure of 3 dB;

- 1 dB of margin is set aside to deal with the potentially destructive signals generated by hybrid terrestrial repeaters.

5.2.1 Illustrative coverage case

The signal path geometry of the DARS system complemented by a terrestrial on-channel repeater is illustrated in Figure 5.1 for increasing values of receiver distance from the terrestrial repeater, also including the relative signal levels and propagation delays in relation to the Transmission Mode II guard interval (62 μsec).

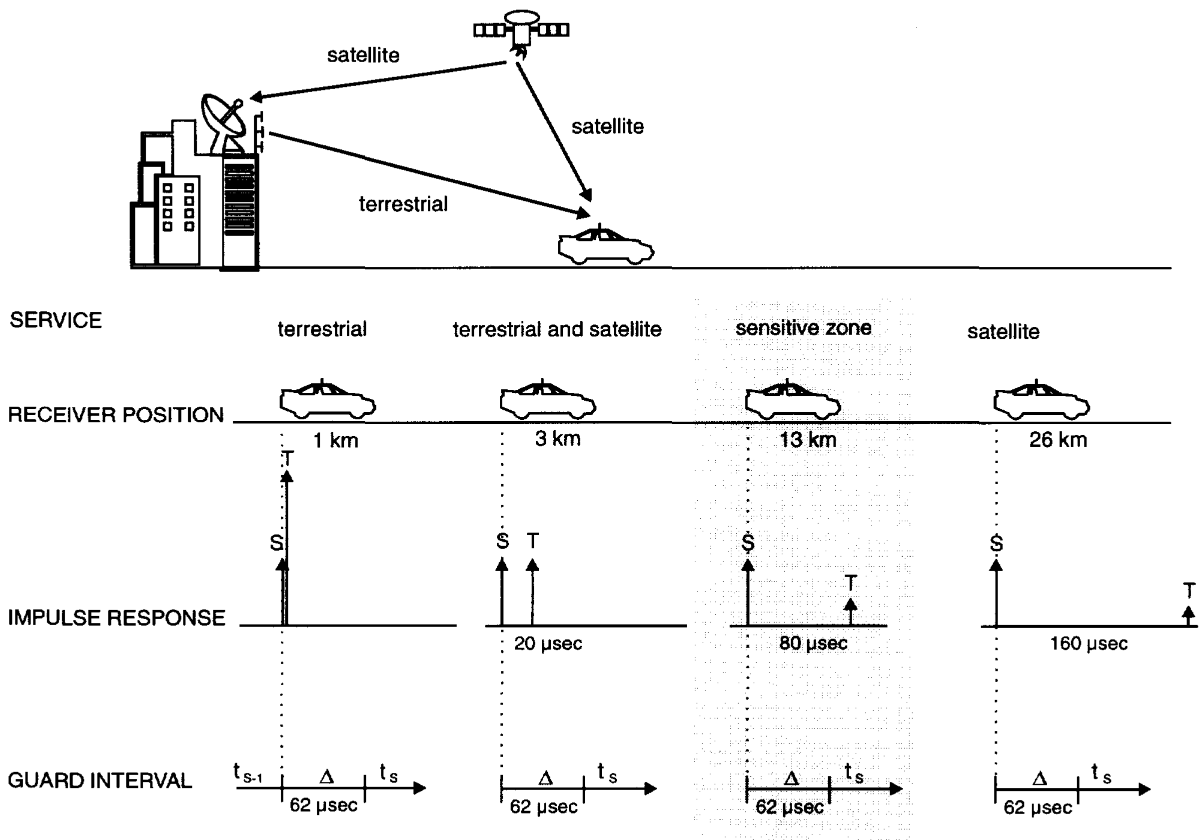

Figure 5.1: Signal path geometry of satellite DAR complemented by a terrestrial on-channel repeater.

In the vicinity of the terrestrial repeater, all signals will be received within the guard interval, such that all signals will be seen as constructive through statistical signal addition. As the receiver moves away from the repeater, some signals start appearing outside of the guard interval and thus can become destructive. In this sensitive zone, the degree of interference will depend on the relative signal levels, and excessive interference will result in coverage gaps or interference areas', appearing near the repeater in the direction of the satellite. It is possible to design the repeaters in such a way that this interference is controlled and has a negligible impact on the service coverage. As the receiver moves further away from the repeater, the interference problem starts disappearing as the repeater signal level becomes sufficiently low relative to the satellite signal level.